A PPM APPLICATION NOTE
Does Twisting Matter?
Or, The Benefits of a Twisted Cable

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January 2005
Revised, October 2005

ABSTRACT

Typical tests performed with an electronic load involve relatively high currents and often require that the load current is turned on and/or off rapidly. Either or both of these conditions place significant performance demands on the electronic load AND THE WIRES CONDUCTING ELECTRICITY FROM THE DEVICE UNDER TEST TO THE ELECTRONIC LOAD. Ideally, making the connecting wires as short and as large as possible eliminates many of the measurement problems introduced by the connecting wires; however, this is not always possible. This Application Note reviews the impacts of connecting wire length and size on the measurement process and introduces some practical means of minimizing the impact of length and size.

I. INTRODUCTION

Fundamentally, an electronic load maintains a specific current flow from a device under test. In its most simple form, an electronic load can be viewed as an electronically controlled variable resistance. This resistance is electronically adjusted to maintain the desired current or other electrical parameter (more on that later).

This simple view is diagrammed in Figure 1. In this figure, the Source (represented by the battery of voltage E) is connected to the Load (represented by the variable resistor) by two wires. The current drawn by the Load (I) is equal everywhere in the circuit. Therefore the same current drawn from the Source flows through both wires, the load resistance (R_L) and the shunt resistance (R_S).

For all practical purposes, the current drawn from the load has a value of: $I = E / R_L$. The shunt resistance is very small when compared to all other resistances in the circuit and therefore has little impact on the total current flow. No matter how small the shunt resistance, the voltage developed across the shunt still obeys Ohms Law and therefore has a value of: $E_S = I \text{ X } R_S$. That small voltage is monitored by the Load's electronic control circuits which, in turn, adjust the value of R_L to maintain the desired current.

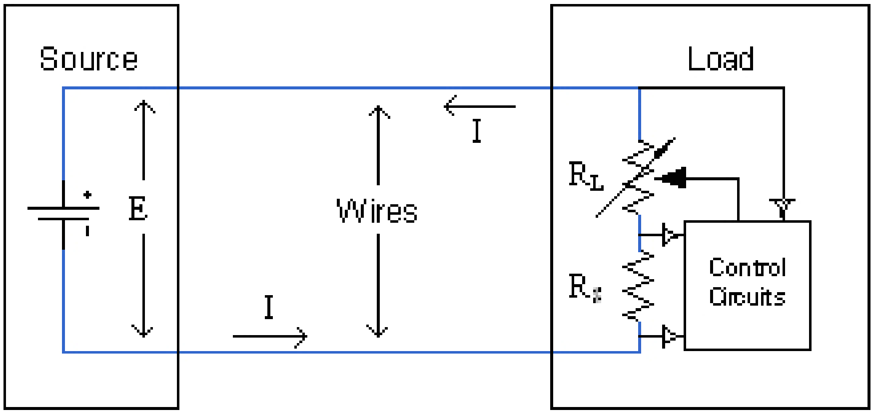


Figure 1 – The basic electronic load

In its most common form, an electronic load is used to maintain a constant current flowing from the source regardless of changes in the source voltage. Therefore, in CC (Constant Current) mode, the control circuit's job is to adjust the value of R_L to maintain the desired current I.

Today's modern electronic loads add circuits to the CC circuits that allow the user to select operating modes where the current is maintained at such a value as to load the source in the CP (Constant Power), CV (Constant Voltage), or CR (Constant Resistance—sometimes referred to as Constant Conductance) modes. In each case, the control circuits measure the current flowing in the circuit and the voltage across the load and use the laws relating current, voltage, resistance and power to adjust the value of R_L to maintain the current, power, voltage or resistance set by the operator.

So ends theoretical operation! Now for some practical issues.

II. CONNECTING WIRE RESISTANCE

In real life, we must deal with a total measurement circuit that looks more like the one diagrammed in Figure 2.

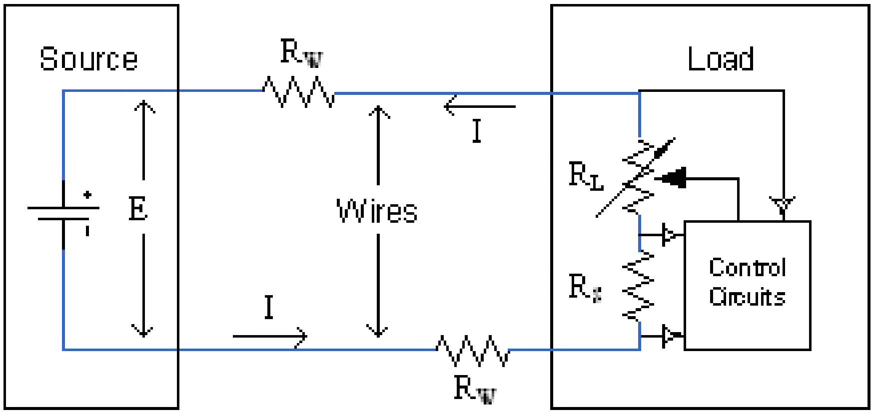


Figure 2 – An electronic load connected to a source via real-world wires

Here we see the addition of resistance from the wires (R_W)—and we note that there is a resistance (typically the same) for each of the two wires that connect the Source to the Load. What is the impact of adding the wire resistance (2 X R_W)? Simply, these resistances cause a voltage drop that has a value of: $E_W = I \text{ X } R_W$ (again, remember this will be times 2 as there is an equal resistance in the wire through which current flows to the Load and in the wire through which current flows back to the Source).

As shown in the figures, the typical electronic load uses the voltage across its input terminals and the current flowing into and out of its input terminals to control the value of the load resistance. Now, however, the voltage at the load's input terminals is equal to the Source voltage MINUS 2 X E_W.

OK—so you use big wires to connect the battery to the electronic load. What harm can a little wire resistance do?

The table in Appendix A shows the values of resistance one can expect to find for various sizes and lengths of copper wire (sizes and length often encountered in practical situations where electronic loads are used to test devices such as batteries, fuel cells, battery chargers, power supplies, etc.).

Let's presume we have connected our Source to our Load with two 10' pieces of #6 copper wire. From the table we see that each wire has a resistance of 3.951 mΩ (get real—approximately 0.004 Ω) for a total extra circuit resistance of 0.008Ω.

Now, let's suppose we are testing our battery to see how it behaves with a 100 Ampere current draw. We find that the voltage loss from the connecting wires has a value of:

$E_{2W} = I \text{ X } R_W \text{ X } 2 = 100 \text{ A X } 0.008\Omega = 0.8 \text{ Volts.}$

So, instead of 12 Volts (the battery voltage) at the Load terminals we find 12.0 – 0.8 volts or 11.2 Volts.

So, what does this matter? Well, in CC mode, not much. After all, we wanted a current of 100 Amperes and 100 Amperes it is. How about CP (Constant Power)? That is a different kettle of fish. In keeping with our 100 Ampere theme, suppose the Load has been set for 1,200 watts (100 Amperes @ 12 Volts). In this case, the Load sees 11.8 Volts not 12 Volts. Therefore it sets a current of 101.7 Amperes (1200 Watts = 11.8 Volts X 101.7 Amperes). The battery, however, is supplying 101.7 Amperes at 12 Volts or 1220.3 Watts—an error of 1.7% in the desired CP setting.

Similar errors occur if you are trying to set the Load in the CV (Constant Voltage) or in the CR (Constant Resistance) modes—errors due to the voltage drop on a short, heavy (10’, #6) wires.

Fairly clearly the solution to this problem lies in the table shown in Appendix A. That is, use a shorter and/or heavier cable. Additionally, it is very important to use clean, tight and low resistance connections—both on the Source and at the Load’s input terminals (see Figure 3). Frequently and usually because it is expeditious, connections to a source such as a battery with lead posts is simply made by hand tightening the connector on the battery terminal. Often, this becomes a high-resistance (remember high resistance here is a relative term which we must compare to an undesirability high cable resistance of 0.008 Ω). Terminals should also be cleaned regularly. Often terminals on batteries are exposed to corrosive vapors released when the batteries are charged/discharged. This corrosion creates a high-resistance (relatively) film on the battery terminal. Likewise, even a copper input connector on the electronic load can oxidize—and copper oxide is also a high resistance material.

Figure 3 – Typical high-current electronic load cable connections

Alternatively (if available) you can use the electronic load's "Remote Sense" feature. When using Remote Sense, the reference voltage is not measured at the Load's input terminals but rather at the Load itself. Although this sounds like a simple solution, it is infrequently used as remote sensing often causes the electronic load to exhibit instability and oscillations if not implemented with great care.

III. CONNECTING WIRE INDUCTANCE

Unfortunately, difficulties with the wires connecting the Source to the Load do not end once we have accounted for the wire resistance. Wires have an additional electrical property called inductance. Inductance is the property of a current carrying conductor that tends to oppose the flow of changing currents in the conductor due to the interaction of changing magnetic fields generated by the changing current with the conductor itself.

A modified view of our Source/Load diagram showing the inclusion of wire inductance is shown in Figure 4. In this figure, the inductance of the connecting wires is shown as L_W.

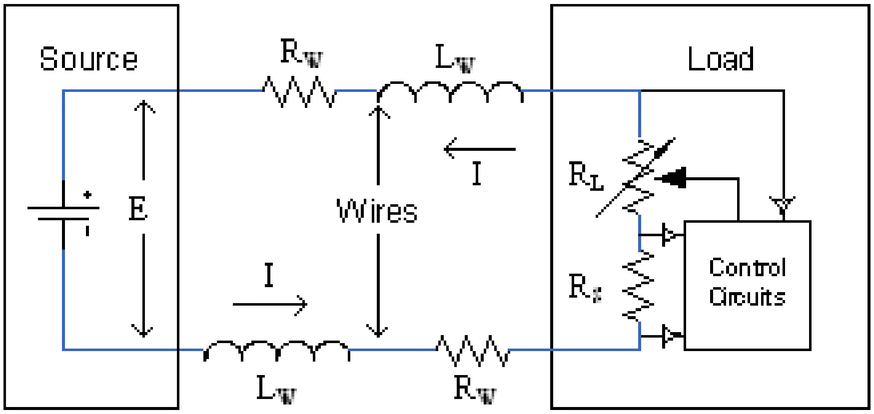


Figure 4 – Connecting the electronic load to a source through wires with inductance

The inductance of electrical wires between the Source and the Load often cause significant measurement problems. This problem, caused by the interaction between a sudden change in current and the wire's inductance, generates an additional voltage across the wire (which therefore also appears at the electronic load as a difference between the Source voltage and the voltage seen by the Load).

The voltage drop across the wires due to their inductance and the change (Δ) in current in the wire can be calculated by the formula:

Δ Voltage over time = Inductance X Δ Current over time

So, does this matter?

Like most things, the answer is maybe. It doesn't matter if the time frame of measurement interest is very great with respect to the time span for the current change. So, for long-term testing, the issue of connecting wire inductance can be ignored—IF THE ELECTRONIC LOAD HAS BEEN DESIGNED TO REMAIN STABLE (i.e not oscillate) WITH AN INDUCTIVE INPUT.

Unfortunately many times we need to perform measurements while the current is changing. Let's look at an example. We return to our 12 Volt battery connected to an electronic load. This time we are not going to have measurement problems caused by too much wire resistance! So, we use two 10' #1 wires. Again, the battery is to be tested at a draw of 100 Amperes.

In this case, #1 copper wire has a resistance of 0.0001239 Ohms/Foot. Therefore, the 20 foot round trip resistance is 0.002478 Ohms. When a current of 100 Amperes is drawn, the voltage drop is:

Voltage = Current X Resistance = 0.002478 Ohms X 100 Amperes = 0.2478 Volts

Thus, the voltage at the input terminals of the electronic load is less than the battery's voltage by an amount equal to the "IR" drop. In this example, this is approximately ¼ Volt out of 12 Volts or just a little over a 2% voltage change—much better than the 0.8 Volt drop from our earlier example with #6 wires.

So, where does inductance come into the picture? A 20 foot length (two 10' lengths) of #1 wire has an inductance of approximately 3 µH (micro Henrys—0.000003 H or 3,000 nH as shown in the table in Appendix B). To keep the arithmetic simple, assume that the 100 Ampere current is switched on so that the change from zero Amperes to 100 Amperes occurs in 1/10,000th of a second (100 µS). Using the formula for voltage developed by a change in current in an inductor we find:

Δ Voltage = Inductance X Δ Current = 3 µH X 100 Amperes /1 µSecond = 3 Volts.

Here we find a change in voltage from the inductance that is approximately10 TIMES the change in voltage from the resistance—and this is if the change in current is leisurely (i.e. occurs in 1/10,000th of a second). More than likely, the change in current will happen in a time between 1/10,000th or 1/100,000th of a second. In the later case, the voltage change from the inductance in the wires would be100 times as great as the change from resistive drop—now we will see a momentary voltage spike at the load input terminals that is nearly 3 times the value of the battery voltage.

Where does this cause a problem? Well, fortunately (and unfortunately as well—swords often have two edges) this is only momentary. However, momentarily, in our example above, the electronic load is attempting to regulate 15 Volts (vs. 12 Volts) to a current of 100 Amperes—and, it must do this very quickly (i.e. in something like 1/10,000th of a second).

If the electronic load is very fast, it can compensate for this spike in input voltage. To the degree that it cannot correct for this rapid change in input voltage, the current drawn will increase in direct proportion to the increase in voltage. So, in this case, an electronic load adjusted to cause a constant 100 Ampere current to flow with 12 Volts applied might allow a current increase to 125 Amperes for a short time (perhaps not the entire 1/10,000th of a second, but for some significant portion of that time). In many situations this results in a significant measurement error. Figure 5 shows how the current in a load might respond to a rapid change. Note the momentary "overshoot" of current immediately following the point in time when the current rapidly changes from zero to its full value.

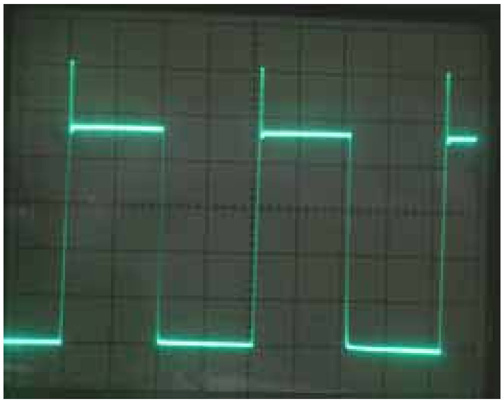


Figure 5 – A current spike or overshoot caused by rapid change in input current.

OUCH!

So, what can be done about this?

Fortunately, inductance is a property of the wires that can be configured to work for us (as well as against us). Again, the property of inductance is caused by the changing magnetic field generated by a wire with a changing current. The changing current develops a changing magnetic field. This changing magnetic field causes an opposite current to flow in the wire. This opposite current, combined with the initial current, reduces the overall current flowing in the wire thus reducing the overall current flow—just like a resistance in the wire would do.

But this can be turned into an advantage. If two wires are in close proximity and the two wires carry equal and opposite currents (the current flowing into the Load and the current returning to the battery), then they generate equal and opposite magnetic fields. These equal and opposite magnetic fields tend to cancel each other out. This interaction between the two magnetic fields is called mutual inductance.

Great! So how do we ensure that these fields cancel each other?

One approach is to simply make sure that the wires carrying current to and from the Load are in close proximity to each other. Lashing them together with cable ties helps. Although this makes a significant difference, measurements will show that there is still a significant amount of the inductance that is not canceled out—and as we have seen, even a small amount of inductance can introduce measurement errors.

So, how do we ensure that we have maximized the use of mutual inductance to reduce the total cabling inductance as much as possible?

Enter the twisted pair—see Figure 6.

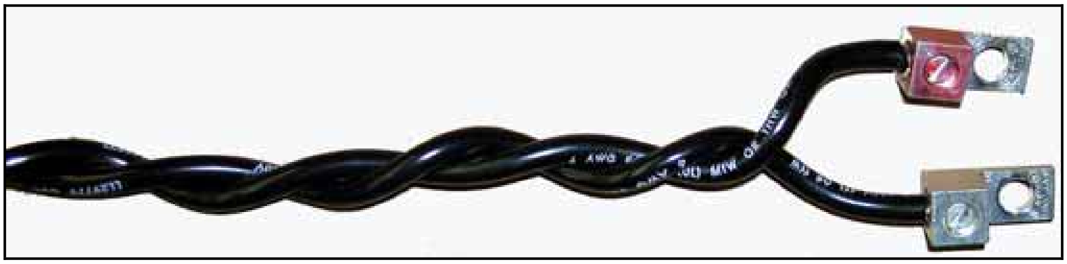


Figure 6 – One end of a #6 twisted pair with a twist of 2.5”

Here are samples of the inductance found when looking into a pair of 32” #6 wires joined at one end (to form a closed loop) but with different physical configurations:

Physical Arrangement	**Inductance**
Circle	1.5 µH
Parallel (spaced about 2” apart)	1.0 µH
Parallel (spaced as closely as the insulation will allow)	0.75 µH
Twisted together (about one twist every 4”)	0.6 µH
Twisted together (about one twist every 2 ½”)	0.48 µH

From the data in the table, we can make the following observations:

- The maximum inductance occurs with a circle (wires are as far apart as possible—i.e. very little interaction between their two magnetic fields)
- As the wires become closer and closer, the total inductance of the two wires decreases
- Twisting the two wires together substantially enhances the effort to decrease the inductance—and the tighter the twist the better (not easy with #6 wire!)

Let’s take a look at another approach.

As a benchmark, the resistance and inductance characteristics for two 32” pieces of # 1 copper wire are: resistance = 0.00012 Ohms per foot for a total resistance of 0.0006 Ω and Inductance of 0.6 µH.

If one builds an equivalent cable by twisting 16 pieces of #10 wire (8 coming and 8 going) into a braided cable, the resistance is also 0.0006 Ω; however, the inductance falls to 0.2 µH. See Figure 7.

Figure 7 – A #1 pair equivalent cable made from twisting 16 pieces of #10 wire.

What does twisting do? Twisting ensures that the magnetic field generated by current traveling in one conductor is, on the average, uniformly coupled into the other wires and therefore ensures the best approximation possible to a balance between the magnetic fields generated by the current that is flowing “into” the load and the current flowing “away from” the load.

If we want to increase the uniformity of the magnetic fields, we use tighter twisting (i.e. more twists per unit length). Additionally, using many smaller wires to make up a cable with the equivalent resistance of a larger wire, simply ensures greater uniformity of the magnetic field and therefore reduces the inductance—and, to some degree—it makes a more flexible (mechanically) cable which can be a real advantage when working with the likes of #1 or larger wires.

Twisting is not the only measure one can take to reduce inductance. The inductance of a conductor is proportional to its length (longer means more inductance), and inversely proportional to its width and proximity to adjacent conductors. So, flat, closely spaced conductors also are low inductance. Laminated bus bars are a good example of such an inductance reducing mechanism; however, they are often difficult to implement physically.

Inductance also increases if the wire is coiled or if there is a magnetic material (like steel or iron) in close proximity to the wire. Therefore, wrapping excess cable around a steel support post to keep the area tidy is not recommended if you want low inductance!

Note: bringing two wires in close proximity to each other does increase the capacitance between the two conductors. Unfortunately, not only is energy stored in magnetic fields, but it is also stored in a capacitor. Fortunately, in the case of most electronic loads, the small amount of increased capacitance that occurs when twisting wires together does not result in a capacitance increase that is meaningful for these types of measurements.

IV. SUMMARY

The performance of an electronic load not only depends on the electrical characteristics of the electronic load itself but also on the wires connecting the source to the load and the quality of the connections themselves. The user must be aware of the impacts of wire resistance and wire inductance, and connection quality. Just how the resistance and inductance will effect measurements is highly dependent on what measurements are being taken.

Additionally, the effect on measurements is also dependent on how well (quickly) the electronic load is able to respond to changes in voltage and current at its input terminals. A load that has the ability to respond quickly to changes in input voltage/current will substantially minimize the impact of wire inductance. The waveform shown in Appendix C demonstrates what can be expected from a fast responding load. It shows how a fast responding electronic load is able to correct for rapid current transitions.

APPENDIX A

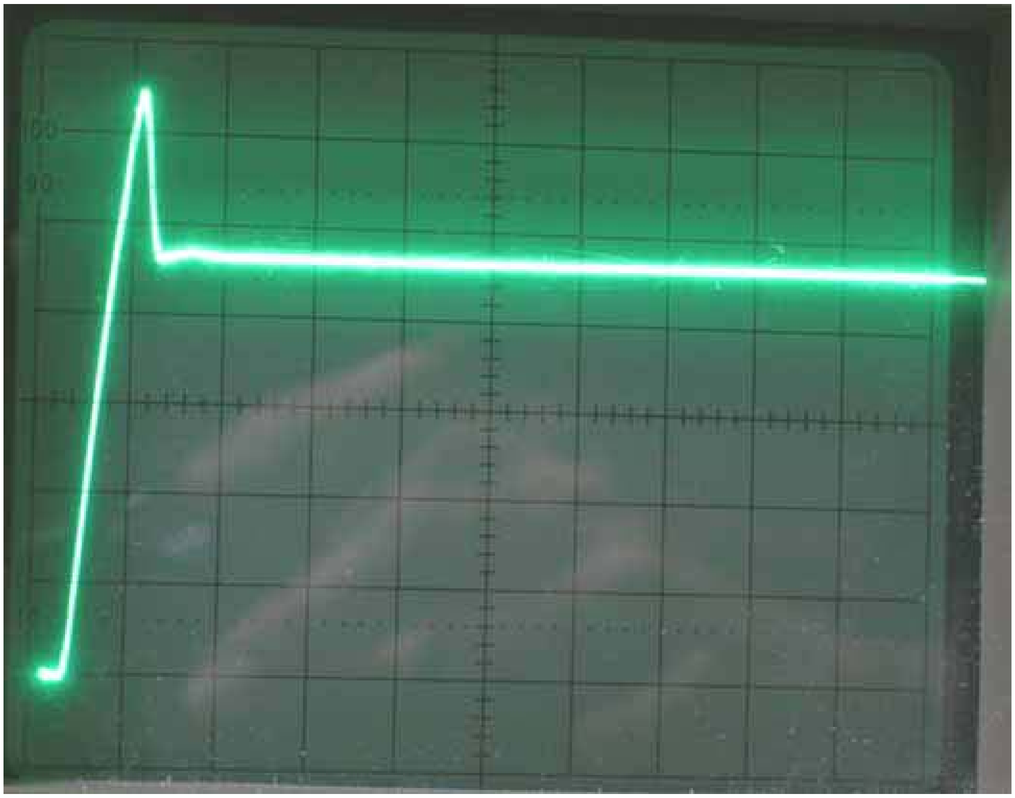
	Resistanceof a Given Length and Size of Copper Wire in MilliOhms												
Wire Size	Wire length Feet/CM												
	1.00	2.00	5.00	10.00	12.00	15.00	20.00	50.00	100.00	150.00	200.00	250.00	300.00
	30.48	60.96	152.40	304.80	365.76	457.20	609.60	1,524.00	3,048.00	4,572.00	6,096.00	7,620.00	9,144.00
4/0	0.049	0.098	0.245	0.490	0.588	0.735	0.980	2.451	4.901	7.352	9.802	12.253	14.703
3/0	0.062	0.124	0.309	0.618	0.742	0.927	1.236	3.090	6.180	9.270	12.360	15.450	18.540
2/0	0.078	0.156	0.390	0.779	0.935	1.169	1.559	3.897	7.793	11.690	15.586	19.483	23.379
1/0	0.098	0.197	0.491	0.983	1.179	1.474	1.965	4.914	9.827	14.741	19.654	24.568	29.481
1	0.124	0.248	0.620	1.239	1.487	1.859	2.478	6.195	12.390	18.585	24.780	30.975	37.170
2	0.156	0.313	0.782	1.563	1.876	2.345	3.126	7.815	15.630	23.445	31.260	39.075	46.890
3	0.197	0.394	0.985	1.970	2.364	2.955	3.940	9.850	19.700	29.550	39.400	49.250	59.100
4	0.249	0.497	1.243	2.485	2.982	3.728	4.970	12.425	24.850	37.275	49.700	62.125	74.550
5	0.313	0.627	1.567	3.133	3.760	4.700	6.266	15.665	31.330	46.995	62.660	78.325	93.990
6	0.395	0.790	1.976	3.951	4.741	5.927	7.902	19.755	39.510	59.265	79.020	98.775	118.530
7	0.498	0.996	2.491	4.982	5.978	7.473	9.964	24.910	49.820	74.730	99.640	124.550	149.460
8	0.628	1.256	3.141	6.282	7.538	9.423	12.564	31.410	62.820	94.230	125.640	157.050	188.460
9	0.792	1.584	3.961	7.921	9.505	11.882	15.842	39.605	79.210	118.815	158.420	198.025	237.630
10	0.999	1.998	4.995	9.989	11.987	14.984	19.978	49.945	99.890	149.835	199.780	249.725	299.670
11	1.260	2.520	6.300	12.600	15.120	18.900	25.200	63.000	126.000	189.000	252.000	315.000	378.000
12	1.588	3.176	7.940	15.880	19.056	23.820	31.760	79.400	158.800	238.200	317.600	397.000	476.400

APPENDIX B

	Inductance of Various Sizes and Lengths of Copper Wires Nano Henrys												
Wire Size	Wire length Feet/CM												
	1.00	2.00	5.00	10.00	12.00	15.00	20.00	50.00	100.00	150.00	200.00	250.00	300.00
	30.48	60.96	152.40	304.80	365.76	457.20	609.60	1,524.00	3,048.00	4,572.00	6,096.00	7,620.00	9,144.00
4/0	59	155	508	1,199	1,497	1,960	2,766	8,127	18,090	28,745	39,849	51,289	62,994
3/0	62	161	523	1,230	1,534	2,006	2,827	8,281	18,397	29,206	40,465	52,058	63,918
2/0	65	167	539	1,261	1,571	2,052	2,889	8,434	18,703	29,665	41,077	52,823	64,836
1/0	68	173	554	1,291	1,608	2,098	2,950	8,588	19,010	30,125	41,690	53,590	65,756
1	71	179	569	1,322	1,644	2,144	3,011	8,741	19,317	30,586	42,305	54,358	66,678
2	74	185	585	1,353	1,681	2,190	3,073	8,895	19,625	31,047	42,919	55,126	67,600
3	77	191	600	1,384	1,718	2,236	3,134	9,048	19,932	31,508	43,533	55,894	68,520
4	80	198	615	1,414	1,755	2,282	3,195	9,202	20,238	31,968	44,147	56,661	69,441
5	84	204	631	1,445	1,792	2,328	3,257	9,355	20,546	32,429	44,762	57,429	70,363
6	87	210	646	1,476	1,829	2,375	3,318	9,509	20,853	32,889	45,375	58,196	71,283
7	90	216	661	1,506	1,865	2,420	3,380	9,662	21,159	33,348	45,988	58,962	72,202
8	93	222	677	1,537	1,902	2,467	3,441	9,815	21,466	33,809	46,602	59,729	73,123
9	96	228	692	1,568	1,939	2,513	3,503	9,969	21,774	34,271	47,217	60,499	74,046
10	99	234	707	1,598	1,976	2,559	3,564	10,122	22,080	34,730	47,830	61,264	74,965
11	102	241	723	1,629	2,013	2,605	3,625	10,276	22,387	35,191	48,444	62,032	75,887
12	105	247	738	1,660	2,050	2,651	3,687	10,429	22,694	35,651	49,058	62,799	76,807

NOTE: Inductances shown in this table are calculated inductances using a commonly accepted formula for the inductance of wires. Actual inductances found in real world applications may vary due to other influences unaccounted for by the formula.

APPENDIX C



50 µsec per division
40 Amperes per division
Pulse 0 to Approx 190 Amperes
Input voltage approximately 12 Volts
This represents a load resistance of 63mΩ
Rise time 0 Amperes to settle at 190 Amperes is approximately 35 µSec

Analysis:
Rise time is 190 Amperes in about 30µSec
That is 190/30 µSec
This computes to about 633,333 Amperes/Sec di/dt

Voltage developed is L*di/dt
Inductance of 1/0 wire @5 feet is 550nH or 550
Voltage developed is 633,333 x 550nH = 3.5 Volts

This voltage will add to the source voltage and increase it to 15.5 Volts.
Instantaneous current will rise to 246 Amperes
If the load is doing its job, this should be recovered quickly. As indicated above in the actual physical example:
Current increased to 256 Amperes in 30 µSec
Power load recovered and controlled to 190 Amperes in less than 10 µSec.

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